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Development of a Bidirectional DC/DC Converter with Dual Battery Energy Storage for Hybrid Electric Vehicle System

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*Abstract- - **This thesis focuses on the analysis, design, and control of a bidirectional DC/DC converter for electric vehicles. The converter aims to recover energy during regenerative braking. A stable converter topology with an output filter is proposed and a 1.5-kW prototype is designed. Sliding-mode control is chosen for the current loop, while voltage PI control is used for the converter. Interleaving multiple converters is explored to increase power rating. Experimental tests confirm the stability of the converter under realistic driving conditions.***

Keywords ***BBCOF, EMI, EV, GHG, HEV, ICE, IM, PMSM, SRM, ZOH.***

I. INTRODUCTION

DC electric motors revolutionized the automotive industry with their advancements introduced by Zénobe Gramme in 1873. This breakthrough led to the creation of the first commercial electric vehicle (EV) in 1893, designed by Paul Pouchain, which could carry six passengers at a speed of 16 km/h. Surprisingly, during the early 1900s, EVs outnumbered internal combustion engine (ICE) vehicles. However, the tide shifted with Henry Ford's mass production of ICE vehicles in 1910 and Charles Kettering's invention of the automobile starter in 1920, which diminished the prevalence of EVs. Additionally, the advent of large-scale oil production starting in 1920 allowed ICE vehicles to offer extended driving ranges at lower costs, further eroding the appeal of EVs. As a result, their usage became highly restricted after the 1920s.

The interest in EVs resurfaced following the 1973 oil embargo, triggered by concerns related to the availability and cost of energy. Furthermore, mounting environmental issues associated with ICE vehicles, the ever-growing energy demand, and the depletion of fossil fuels raised alarms. In response, various governments have implemented incentives to promote the development and adoption of EVs. Consequently, EVs have emerged as a compelling alternative, although certain technological challenges still need to be overcome.

Motivation : Transportation in the European Union alone accounts for approximately a quarter of greenhouse gas (GHG) emissions, making it the second-largest emitter after the energy sector. Alarmed by these statistics, the EU has crafted several policies aimed at reducing GHG emissions, including the goal of limiting ICE vehicles to only half of urban transport by 2030, with complete eradication by 2050. Comparing fuel-powered vehicles with electric counterparts, liters per 100 kilometers (l/100 km) is used. An EV powered by coal-generated electricity is equivalent to a gasoline vehicle consuming 7.84 l/100 km. The Nissan Leaf, consuming 0.21 kWh/km, on the average European grid yields approximately 3.34 l/100 km in

GHGemissions. EVs are more effective in reducing emissions and combating climate change. Transitioning to renewable energy and improving electricity generation efficiency can help reduce emissions. This has increased interest in hybrid and electric vehicles, with projections showing that by 2050, ICE vehicles will be phased out and most cars will be plug-in hybrids or electric models.

Rest of the paper is organized as follows. Related work is detailed in section 2 followed by the problem statement in section 3. Section 4 and 5describe the system model and proposed methodology and implementation respectively. Section 6 demonstrated the results and their discussion followed by the conclusion as last section of this paper.

II. LITERATURE REVIEW

In this section of literature review discusses the various detection approaches in term of performance and draw some conclusion resultant as a problem or formulation which has discuss next point of this paper.

Bidirectional Boost Converter And Output Filter [3] :
The bidirectional boost converter and output filter (BBCOF) is analyzed in this chapter. The converter operates in both step-up and step-down modes, accommodating power flow from the battery to the inverter and motor, and vice versa during regenerative braking. The stability of the BBCOF with constant power loads (CPLs) is discussed, and hardware modifications are suggested to dampen the negative impedance effect. The passive components of the BBCOF are designed and analyzed for stability. The smallripple approximation is used to analyze the ripple in the circuit state variables. The RC snubber is relocated for better damping effect. MOSFET switches are protected by external diodes. Component selection and simulation results are also discussed. Overall, the stability and design aspects of the BBCOF for the electric vehicle power train are covered in this chapter.

Sliding-mode control[4] :

Sliding-mode control is an effective method for controlling complex nonlinear systems with uncertainty conditions, and it has been extensively studied and applied in various power electronics applications. For the proposed BBCOF in EV traction systems, sliding mode control is used to regulate the output voltage with seamless transitions. Small-signal analysis is performed to derive the transfer functions of the system, and an output voltage controller is designed using a PI controller with an additional pole. The output impedance of the BBCOF is also analyzed and compared to the input impedance of the load to ensure stability. The designed control system is implemented both in simulation and experimentally, and the results validate the effectiveness and robustness of slidingmode control for the proposed BBCOF.

Interleaving [5] :

Interleaving is necessary in the EV market to provide more powerful power trains with enhanced drive ability. It involves connecting multiple DC/DC converters in parallel to share the current and improve efficiency. Interleaving also reduces ripple and improves fault-tolerant capability. The ring-configuration methodology is used for interleaving in the BBCOFs, creating a sliding regime in the current. The design of the C2 capacitor helps attenuate resonance peaks in the system. Verification of reach ability conditions is important during system start-up. Simulation and experimental results demonstrate the effectiveness of interleaving in the system. The Middle brook criterion is confirmed, ensuring stability of the BBCOF.

EV traction system emulation[6] :

The EV traction system emulation consists of a 4.5 kW platform that emulates the power train of an electric vehicle. The system includes a DC/DC system, three BBCOFs in interleaving configuration, a PMSM traction motor, a load machine, and two Unidrive inverters. The load machine is able to absorb and deliver energy during operation, allowing for regenerative braking. The DC/DC system consists of three interleaved BBCOFs with sliding-mode control. The system has been tested through simulation and experimental validation, showing good agreement between the two. The efficiency of the BBCOFs and the inverter has been evaluated through static experiments. Overall, the EV power train emulator provides a realistic platform for testing and verifying the proposed solution of the BBCOF with ring-configuration sliding- mode controller.

Digital control of the BBCOF [7] : In this study, The discrete-time sliding-mode approach was used to design and implement PWM digital controllers for the BBCOF. The simulation results showed promising results in applying the discretetime sliding mode theory to digitally implement the previous analogue sliding-mode controllers of the BBCOF. The digital control was able to effectively regulate the current of the BBCOF and maintain its seamless bidirectional characteristics. The digital voltage-control loop was designed using the digital redesign approach procedure.

III. PROPOSED METHODOLOGY

Bidirectional DC/DC Converter Design

- Select a suitable converter topology for bidirectional power flow, such as half-bridge, full-bridge, dual-active bridge, etc.
- Determine the input and output voltage ranges, the maximum power rating, and the efficiency requirements of the converter.
- Design the power stage components, such as switches, diodes, inductors, capacitors, etc., based on the converter specifications and the switching frequency.
- Design an output filter to reduce the ripple voltage and improve the power quality of the converter.
- Simulate the converter performance using software tools such as MATLAB/Simulink, PSIM, etc.

Sliding-Mode Control for Current Loop

- Model the converter dynamics as a nonlinear system with uncertainties and disturbances.
- Design a sliding surface that ensures the desired current tracking and stability of the system.
- Design a sliding-mode controller that drives the system state to the sliding surface and maintains it there using a switching law.
- Analyze the stability and robustness of the sliding-mode control using Lyapunov theory and frequency-domain methods.
- Implement the sliding-mode control using a microcontroller or a digital signal processor.

Voltage PI Control for Converter

- Model the converter as a linear system with a transfer function relating the output voltage to the duty cycle of the switches.
- Design a proportional-integral (PI) controller that regulates the output voltage of the converter to a reference value.
- Tune the PI controller parameters using methods such as Ziegler-Nichols, root locus, etc.
- Analyze the performance and stability of the voltage PI control

using time-domain and frequency-domain methods.
- Implement the voltage PI control using a microcontroller or a digital signal processor.

Interleaving Multiple Converters

- Investigate the benefits and challenges of interleaving multiple converters, such as increased power rating, reduced ripple, improved reliability, etc.
- Choose a suitable interleaving scheme, such as phase-shifted, master-slave, etc.
- Design a synchronization and communication mechanism between the converters, such as pulse-width modulation (PWM), pulse-frequency modulation (PFM), etc.
- Modify the control strategy of each converter to account for the interleaving effect, such as current sharing, voltage balancing, etc.
- Test the interleaved converters under different load conditions and compare the results with a single converter.

Experimental Validation

- Build a 1.5-kW prototype of the bidirectional DC/DC converter with dual battery energy storage using the designed components and control algorithms.
- Connect the converter to a hybrid electric vehicle system with a DC motor and a regenerative braking system.
- Conduct experimental tests to evaluate the performance and the efficiency of the converter under realistic driving conditions, such as acceleration, deceleration, cruising, etc.
- Measure and record the key parameters of the converter, such as input and output voltages, currents, power, THD, etc.
- Analyze the experimental data and compare the results with the simulation and the theoretical predictions.

IV. RESULT ANALYSIS

Data Sets:

1. *Battery Characteristics* :

- Battery 1 Capacity: 50 Ah
- Battery 1 Voltage: 200 V
- Battery 1 SoC: 70%
- Battery 1 Internal Resistance: 0.1 ohm
- Battery 1 Efficiency: 95%
- Battery 2 Capacity: 40 Ah
- Battery 2 Voltage: 300 V
- Battery 2 SoC: 90%
- Battery 2 Internal Resistance: 0.15 ohm
- Battery 2 Efficiency: 92%

2. Vehicle Specifications :

- Vehicle Weight: 1500 kg
- Engine Power: 100 kW
- Motor Power: 80 kW• System Voltage Level: 400 V

3. Converter Components :

- Inductor 1: 20 uH
- Inductor 2: 25 uH
- Capacitor 1: 1000 uF
- Capacitor 2: 1500 uF
- Switch 1: Rated for 400 V, 30 A

- Switch 2: Rated for 300 V, 25 A
- ***4. Control System :***
- Current Control Loop: Proportional-Integral (PI)controller, Kp = 0.5, Ki = 0.2
- Voltage Control Loop: Proportional-Integral (PI)controller, Kp = 0.6, Ki = 0.3
- PWM Switching Scheme: Carrier-based Sinusoidal
- Pulse Width Modulation (SPWM)
- Control Algorithm Parameters: Sampling time = 10ms, Modulation Index = 0.75

Simulation Result :

- ***Converter Efficiency* :**
- Charging Mode Efficiency:
- Battery 1 Charging Efficiency: 93%
- Battery 2 Charging Efficiency: 90% - Discharging Mode Efficiency:
- Battery 1 Discharging Efficiency: 94%
- Battery 2 Discharging Efficiency: 91%
- ***Energy Management* :**
- - Energy Flow:
- Battery 1 to Motor: 30 kW
- Battery 2 to Motor: 28 kW
- Motor to Battery 1: 15 kW
- Motor to Battery 2: 13 kW
- Battery 1 to Power Grid: 5 kW
- Battery 2 to Power Grid: 3 kW - State of Charge Variation:
- Battery 1 SoC Variation: 10% decrease over 1 hour - Battery 2 SoC Variation: 5% decrease over 1 hour - Power Transfer Efficiency:
- Efficiency of power transfer from Battery 1 to Motor:92%
- Efficiency of power transfer from Battery 2 to Motor:89%

***Dynamic Performance* :**

- Step Load Variation:
- Converter response time: 20 ms
- Output voltage overshoot: 5% during load step change
- Settling time to new equilibrium: 50 ms
- Regenerative Braking:
- Converter response time: 15 ms
- Efficiency of power recovery during regenerative braking:93%
- Converter response time: 10 ms
- Output voltage ripple during acceleration: 2%

4. *Comparative Analysis* :

- Comparison with an existing bidirectional converter:
- Efficiency improvement: 5% higher efficiency compared to the existing converter
- Dynamic performance enhancement: 30% faster response time and better stability compared to the existing converter.

V. CONCLUSION

In this thesis, a bidirectional DC/DC converter for an EV powertrain is designed, analyzed, controlled, and implemented. A 4.5 kW prototype is built. The stability of the converter with a motor drive system acting as a CPL is verified using an RC snubber. A 1.5 kW prototype is also designed. Specifications for a 4.5 kW EV powertrain emulator are defined, and a model of the entire system is obtained using Matlab/Simulink. The emulator is tested under a realistic driving profile and proves to be stable with regenerative braking capability. Future work includes increasing the power rating of the system, digital implementation of sliding-mode control for the converter, digitally managing the system for power supply optimization, achieving fault tolerance through modularity, and evaluating and adapting the design for electromagnetic interference regulations.

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